Compressional Wave Velocities in Basic Rocks

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ABSTRACT: Compressional wave velocities determined by measurement of travel times of pulses at pressures to 10 kilobars are given for specimens of basalt. Variations of velocity with propagation direction are related to feldspar orientation and inhomogeneity in alteration of the specimens. Velocity differences reported for diabase, gabbro, eclogite, and basalt can be explained in terms of variation of density and mean atomic weight. The basalts have the lowest compressional wave velocities of basic rocks. The low velocities are a consequence of slight alteration, high mean atomic weight, and relatively low density.

Ultrasonic measurements of the elastic properties of rocks are required for the interpretation of seismic velocities. Comparisons of seismic velocities with laboratory-measured velocities provide the simplest and most direct evidence concerning the constitution of the earth's interior. It is surprising that with the abundant velocity data now available very little attention has been given to basaltic rocks at high pressures. In this paper compressional wave velocities are reported at pressures to 10 kb for three specimens of basalt. In addition to presenting new velocity data which may be important for oceanic crustal areas, this note is part of a continuing effort to understand the factors which influence the elastic properties of rocks.

MEASUREMENT TECHNIQUE

The technique for measuring the velocities was similar to that described by Birch (1960) and Christensen (1965); therefore it is described only briefly here. The specimens were cylindrical cores, ⅝ inch in diameter and 2 inches in length, jacketed with a thin copper tube. Barium titanate transducers with natural frequencies of 1 Mc/sec were placed on the ends of the specimens and then backed by aluminum electrodes. Rubber tubing was used to seal the pressure fluid from the spaces between the sample, electrodes, and transducers. Rectangular electrical pulses of about 50 volts were applied to one transducer. The resulting mechanical pulse in the sample was received by an identical transducer and converted to an electrical signal which was amplified and displayed on a dual-trace oscilloscope. Transit times were measured by comparing the signal from the rock specimen with that through a variable mercury delay line displayed simultaneously on the oscilloscope.

Kerosene was used as the pressure fluid. Pressure was generated by the advance of a piston driven by a 6-inch ram into a cylinder with an outside diameter of 6 inches and an inside diameter of 1.5 inches. Pressure was measured by determining the change in resistance of a calibrated manganin wire gage. All measurements were made at temperatures between 20° and 30°C.

DATA

Compressional wave velocities and densities are given in Table 1. Velocities are recorded for each specimen from three cores cut in mutually perpendicular directions. The velocities are considered accurate to 1%.

The basalts were collected from the Triassic Hampden basalt near Hartford, Connecticut. Petrologically they are fine-grained tholeiitic basalts. Average grain size is about 0.2 mm. Modal analyses are given in Table 2.

DISCUSSION

Anisotropy in the basalts is related to variations in composition of the three cores from each sample and a subparallel orientation of plagioclase laths. Directions of low velocity in

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TABLE 1

Compressional Wave Velocities in Basalt
(km/sec)

SAMPLE	DENSITY (g/cc)	PRESSURE (kb) 0.1	0.5	1.0	2.0	4.0	6.0	8.0	10.0
Basalt 1	2.91	5.8	6.03	6.08	6.13	6.21	6.25	6.28	6.33
	2.91	5.9	6.05	6.11	6.15	6.23	6.28	6.32	6.37
	2.88	5.6	5.76	5.86	5.97	6.03	6.10	6.16	6.20
Mean	2.90	5.8	5.95	6.02	6.08	6.16	6.21	6.25	6.30
Basalt 2	2.92	5.8	6.00	6.03	6.06	6.11	6.16	6.20	6.25
	2.91	5.8	6.04	6.07	6.09	6.14	6.20	6.24	6.28
	2.91	5.9	6.08	6.14	6.19	6.22	6.27	6.36	6.35
Mean	2.91	5.8	6.04	6.08	6.11	6.16	6.21	6.27	6.29
Basalt 3	2.95	6.0	6.14	6.19	6.25	6.34	6.36	6.42	6.46
	2.92	5.9	6.09	6.16	6.21	6.27	6.34	6.36	6.39
	2.94	6.0	6.11	6.17	6.25	6.29	6.34	6.38	6.42
Mean	2.94	6.0	6.11	6.17	6.24	6.30	6.35	6.39	6.42

TABLE 2

Modal Analyses of Basalts
(Percentages by Volume)

ROCK	PLAGIOCLASE	PYROXENE	MAGNETITE	CALCITE	SERICITE + CHLORITE
Basalt 1	53.4	26.5	7.2	3.2	9.7
Basalt 2	54.2	25.3	6.9	3.0	7.6
Basalt 3	55.8	30.2	6.9	2.6	4.5

basalts 1 and 3 correspond to cores of relatively low density. The low densities are the result of slight alteration of pyroxene to chlorite and sericitization of plagioclase. No preferred orientation of minerals was observed in either sample. Petrographic examination of basalt 2 revealed a rough subparallel orientation of lath-shaped plagioclase crystals. Normals to the (010) twin planes of plagioclase concentrate in the direction of highest velocity. This is consistent with relatively high compressional wave velocities normal to (010) in single crystals of feldspar reported by Christensen (1966*a*).

Manghnani and Woollard (1965) have correlated elastic wave velocities in basalts at low pressures with glass content, olivine content, and volume percent of vesicles. The samples in the present study contain no microscopically visible glass or vesicles. Therefore, with the exception of a slight lowering of velocity due to alteration, the samples represent nearly maximum velocities for olivine-free basalts with tholeiitic composition. As will be considered in detail below, the basalts have lower velocities than other varieties of basic rocks. It is somewhat surprising that compressional wave velocities in several granites reported by Birch (1960) are close to the velocities of the basalts at equivalent pressures. The basalt velocities are also equivalent to partially serpentinized peridotites containing approximately 50% serpentine (Christensen, 1966*b*).

Birch (1961) found a difference in velocity of about 5% between the means for diabase and gabbro. This difference presented a problem since the reported densities were about the same, and diabase and gabbro are generally considered to be approximately equivalent in chemical composition. Birch (1961) and Christensen (1965) postulated that the discrepancy may actually be the result of differences in chemical composition of the two rock types.

The mean compressional wave velocity at 10 kb for the 9 cores of basalt is 6.34 km/sec. This is 0.52 km/sec lower than the mean reported by Birch (1961) for 15 specimens of diabase and 0.87 km/sec lower than the mean for 9 specimens of gabbro. The relatively low velocities of the basalts are due in part to their low densities. This is illustrated in Figure 1, where 10 kb velocities have been plotted against densities for eclogites, gabbros, diabases, and basalts reported by Birch (1960), Kanamori and Mizutani (1965), and this paper.

Birch (1961) has shown that compressional wave velocity is not a single-valued function of density, but also depends upon the mean atomic weight (*m*) of a rock. Birch's straight line solutions for mean atomic weights of 21 and 22 are shown in Figure 1. The points in Figure 1 suggest that important chemical differences (i.e., different values of *m*) which influence elastic properties may be present in basic rocks. Eclogites and basalts appear to have relatively high values of mean atomic weight. Lower values are suggested for diabases and gabbros.

Mean atomic weights calculated from chemical analyses are highest for basalts and eclogites and lowest for gabbros. In Table 3 values of *m* have been calculated from average chemical analyses for basalts, gabbros, diabases, and eclogites. Since the mean atomic weight of a rock is usually a measure of its iron content (Birch, 1961), total iron contents calculated from the reported percentages of FeO, and Fe_2O_3 are also given for the rocks in Table 3.

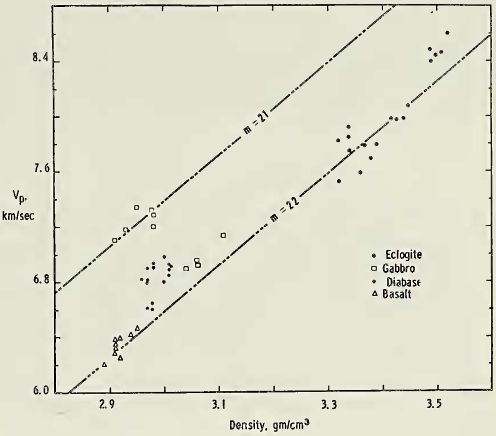

FIG. 1. Velocity at 10 kilobars versus density for basic rocks.

Figure 1 and Table 3 show that Birch's correlation of compressional wave velocity with density and mean atomic weight holds remarkably well for basic igneous rocks. Basalt, which is free of glass and vesicles, falls near the line for $m = 22$. This agrees with chemical analyses of basalt. Laboratory measured velocities and chemical analyses of eclogite also suggest mean atomic weights near 22. Lower mean atomic weights and intermediate densities of gabbros and diabases produce compressional wave ve-

TABLE 3

MEAN ATOMIC WEIGHTS OF BASIC ROCKS

ROCK	MEAN ATOMIC WEIGHT	PERCENT TOTAL IRON	REFERENCE
Norite	21.5	6.71	Nockolds (1954)
Pyroxene gabbro	21.6	7.33	Nockolds (1954)
Gabbro	21.7	6.83	Clarke (1966)
Olivine gabbro	21.7	7.70	Nockolds (1954)
Hornblende gabbro	21.8	7.99	Nockolds (1954)
Diabase	21.8	8.72	Clarke (1966)
Olivine diabase	21.9	9.03	Clarke (1966)
Tholeiitic olivine basalt	21.9	9.23	Nockolds (1954)
Tholeiitic basalt	22.0	9.05	Nockolds (1954)
Olivine-rich alkali basalt	22.1	9.74	Nockolds (1954)
Plateau basalt	22.1	10.10	Clarke (1966)
Alkali basalt without olivine	22.2	8.76	Nockolds (1954)
Alkali basalt	22.2	8.99	Nockolds (1954)
Eclogite	22.2	10.58	Coleman et al. (1965)

locities which are higher than basalts and lower than eclogites. Lower velocities of diabases compared with gabbros are primarily related to differences in chemical composition.

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